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MODELING OF THE NON-AUDITORY RESPONSE TO BLAST OVERPRESSURE

Considerations in Developing a Mechanistically-Based Model
of Blast-Induced Injury to Air-Containing Organs

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James H. Stuhmiller

JANUARY 1990

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In order to anticipate the potential for injury in a wide variety of blast environments, without the excessive use of animal tests, it is necessary to develop a mechanistic understanding that can be used reliably. The process by which the blast wave produces injury is conceived to have the following intermediate steps. The external blast creates a pressure load distribution on the body that sets it in mechanical motion. That motion is transmitted through the body structure to the air-containing organs, where rapid distortions cause stresses within the organ tissue. The combination of stress and motion does work on the tissue and, when certain material limits are exceeded, results in injury. Multiple, isolated exposures lead to a nonlinear accumulation of damage.

This paper discusses the non-organ-specific aspects of modeling this process and demonstrates that the general characteristics of injury observed in animal field tests can be explained. Injury to the larynx is used to make a quantitative validation and a simple-wave, multiple-shot Damage-Risk Criterion (DRC) is developed.

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CONSIDERATIONS IN DEVELOPING
A MECHANISTICALLY-BASED MODEL OF
BLAST-INDUCED INJURY
TO AIR-CONTAINING ORGANS

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ABSTRACT

In order to anticipate the potential for injury in a wide variety of blast environments, without the excessive use of animal tests, it is necessary to develop a mechanistic understanding that can be used reliably. The process by which the blast wave produces injury is conceived to have the following intermediate steps. The external blast creates a pressure load distribution on the body that sets it in mechanical motion. That motion is transmitted through the body structure to the air-containing organs, where rapid distortions cause stresses within the organ tissue. The combination of stress and motion does work on the tissue and, when certain material limits are exceeded, results in injury. Multiple, isolated exposures lead to a nonlinear accumulation of damage.

This paper discusses the non-organ-specific aspects of modeling this process and demonstrates that the general characteristics of injury observed in animal field tests can be explained. Injury to the larynx is used to make a quantitative validation and a simple-wave, multiple-shot damage-risk criterion (DRC) is developed.

CONTENTS

ILLUSTRATIONS

1. BACKGROUND

Direct exposure to blast can result in injury to the air-containing organs of the body: the larynx, lung, gastro-intestinal tract, and tympanic membrane. The ability of these organs to readily change volume leads to rapid distortions in the surrounding tissue which, in turn, produces the injury.

In occupational exposures, the blast levels are relatively low, but there may be many repeated exposures. In these cases, concern is mainly that a chronic condition could develop. A criterion of safety is required for personnel in training. Military Standard 1474B provides the current guidelines [1], but the limits for nonauditory injury were set without the benefit of specific data and may be overly conservative.

During combat, troops may be exposed to large, single blasts. In this case, concern is for acute injury that can incapacitate the soldier. On one hand, there is a need for criteria to define hazardous circumstances that can be avoided, and on the other, there is a need to estimate probable internal injury for combat casualty care.

To meet these needs, animal tests have been conducted to develop an empiric Damage-Risk Criterion (DRC). The animal of choice has been sheep both because of its similarity in size to man and because a considerable amount of data already exists on its exposure to long-duration blast waves. This empiric DRC provides a more satisfactory safety limit [2].

Despite the success of the animal tests, there is a need for a theoretical understanding of the process that leads to injury. Use of animals to estimate human consequences is always subject to uncertainty because of the inevitable differences between species, for example, man stands erect, while the sheep is horizontal, and the sheep has a large amount of gas in the abdomen that man does not. In addition, it is desirable to reduce the number of animals that must be sacrificed and to gain the maximum amount of information from each test that is made. Finally, to develop an empiric DRC for complex wave environments would require an enormous amount of animal testing since there are so many degrees of freedom to consider. A theoretical understanding would identify the significant parameters which could be confirmed with a smaller number of tests.

Models of the biological response to blast have been developed and successfully used in the past. Bowen, et al. [3] modeled the thorax cavity as a single gas volume that could be compressed by pistons representing the chest wall and abdomen. The model was successful in predicting the intrathoracic pressure when the body was exposed to very long duration blasts. This model underpredicts the pressures for short duration loads because it does not capture the parenchymal wave that is produced. Clemedson proposed a similar model for small animals [4].

Both models correlate injury with the maximum pressure in the air during compression. While this is a measure of the magnitude of the body motion, it does not directly give the stresses that do damage to the tissue.

1

In order to develop a satisfactory understanding of the injury process, JAYCOR is developing biomechanical models for the sheep and man under a research project sponsored by the U.S. Army Medical Research and Development Command and the Walter Reed Army Institute of Research. The approach includes multi-dimensional structural analyses of the thorax and abdomen to produce a mechanically correct description of the blast-induced motion. Laboratory experiments are being used to provide direct observation of the injury process and special biological materials testing is providing critical material properties. The models are being validated against field data in which detailed mechanical properties are measured.

The considerations guiding the development of this model are described in this paper. Those concepts are presented in the form of a generic model, that is, one which has the same formalism as the organ-specific models but is greatly simplified.

In addition to providing an overview of the methodology, there are several reasons for applying the generic model directly to the prediction of laryngeal injury. First, the larynx has a structural form which lends itself to a simple mechanical description. Second, an extensive data base of animal tests has already been developed so that it is possible to validate the concepts with some confidence. Finally, those animal tests have shown that the larynx is the most easily damaged of the four organs and so will be used as a precursor of other non-auditory injury. A theoretical basis for the empiric DRC will help guide tests being conducted to extend its range of validity.

2. THEORETICAL CONSIDERATIONS

The process by which the external blast wave produces injury is conceived to have the following, intermediate steps:

1. Blast → Loading

2. Loading → Body Motion

3. Body Motion → Organ Stress

4. Organ Stress → Injury

The subdivision of the process reflects the distinctly different physical phenomena at work. Each step can be validated on its own merits. The goal of the methodology is to provide mechanistically correct descriptions of each step that, taken together, allow environmental conditions to be translated into estimates of injury. The following sections discuss approximate models for each step.

LOADING

The simplest blast environment is that due to a spherical explosive charge set off far from reflective surfaces or a hemispherical charge set of at a flat ground plane. In both cases, the blast wave produced has a self-similar form that has been well studied by a number of investigators [5,6]. A mathematical form that approximates both the incident and reflected pressure time histories is the Friedlander representation

$$p(t) = P(1 - t/t_0) \exp(-bt/t_0)$$

where the parameters P, t_0, and b depend on the energy of the explosive and the distance to point of interest.

Field data is usually reported in terms of peak pressure, P, positive duration, t_0, and positive impulse, I. From these the exponential coefficient, b, can be determined by solving the transcendental relation

$$\frac{I}{Pt_0} = \frac{1}{b}\left[1 - \frac{1 - e^{-b}}{b}\right]$$

Baker [5] has provided tables of parameters for the incident and reflected waves that will be used in this paper. Because of the order used in solving the final model equations, certain rearrangements of those relations are required. First, it is convenient to simplify the representation of b. Figure 1 shows the variation of the normalized impulse over the range of distances quoted by Baker. It can be seen that a constant value of b approximates the ratio over the region of interest. In the course of the solution it is necessary to determine the incident peak pressure from the reflected peak value. Figure 2 shows that the function

$$P_s/P_r - 0.5 \frac{1 + 0.2r}{1 + r}$$

provides a reasonable fit to the data where

$$r = (P_r/P_a)^{0.8}$$

and P_a is the ambient atmospheric pressure. Finally, we shall assume that the positive duration of the incident and reflect waves are identical. Baker's data shows some irregular differences at very short durations, but he suggests that the two are the same generally.

It should be noted that strong explosions at finite heights of burst produce a mach shock as a result of the nonlinear interaction between the incident and reflected waves. There is little data available on this kind of blast and the correlations suggested above may have to be modified. The same general trends, however, are expected to apply.

BODY MOTION

The four air-containing organs of interest (larynx, lung, gastro-intestinal tract, and tympanic membrane) are contained within different body structures (neck, thorax, abdomen, and auditory canal). On the simplest level, however, these structures have inertia, develop opposing forces when distorted, and dissipate energy delivered. Consequently, we adopt the damped harmonic oscillator as a generic model of the structural dynamics of the body. When this system is driven by the reflected blast wave, we have the equation of motion

$$m x'' + 2\gamma x' + k x = P(1 - t/t_0) \exp(-bt/t_0)$$

where m is the mass/area, γ is the damping force coefficient, and k is the effective spring constant/area. The equation can be cast in a dimensionless form by defining new variables

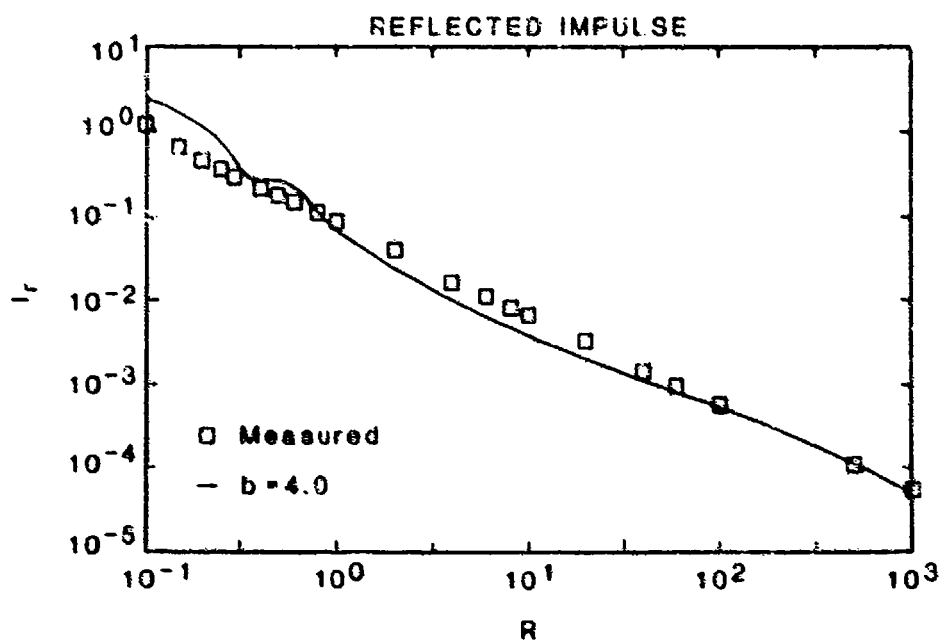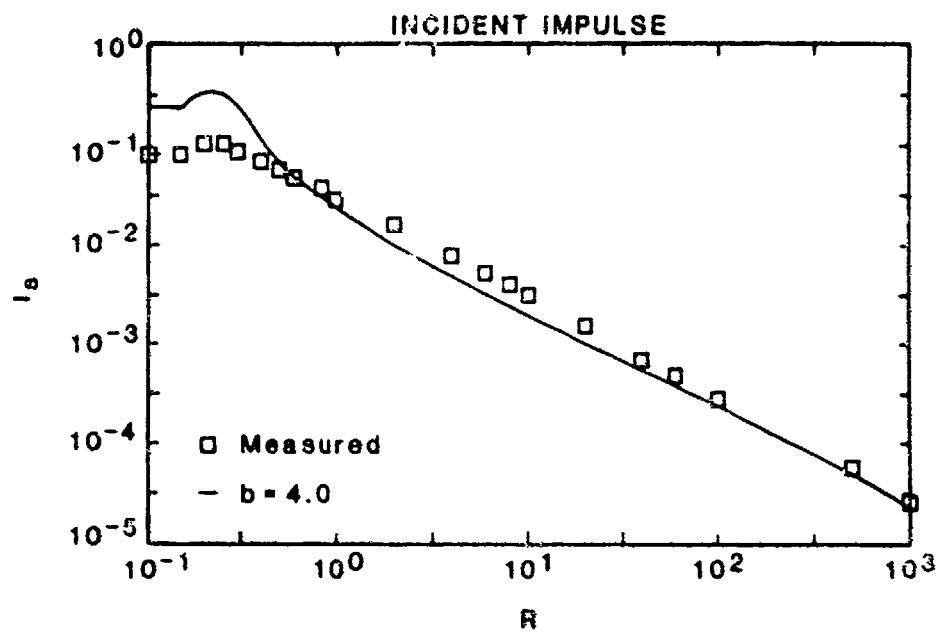$$x = (P/m) t_0^2 X(T)$$

$$t = t/t_0 .$$

Figure 1. Comparison of measured data for the normalized incident and reflected positive impulses with value predicted by a constant exponential factor in the Friedlander representation.
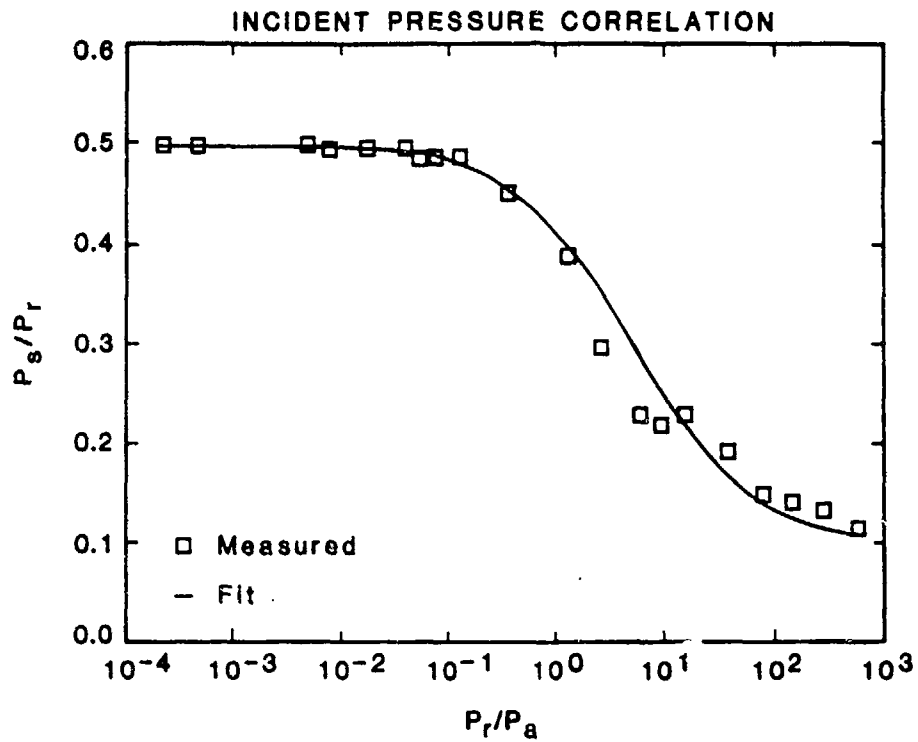
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Figure 2.   Correlation of the incident to reflected peak pressure ratio with the function

$$P_s/P_r = 0.5 \; \frac{(1 + 0.2r)}{(1 + r)}$$

where

$$r = (P_r/P_a)^{0.8}$$

defining the quantities

$$\omega = \sqrt{k/m}$$

$$t_d = m/\gamma \ ,$$

and introducing the parameters

$$\alpha = t_0/t_d$$

$$\beta = \omega t_0 \ .$$

the resulting equation is

$$X'' + 2\alpha X' + \beta^2 X = (1-T) \exp(-bT) \ .$$

The solution of this equation, for which the body is initially at rest, is

$$X(T) = (A - BT)\exp(-bT) + [C \sin(\Omega T) + D \cos(\Omega T)]\exp(-\alpha T)$$

where

$$\Omega^2 \quad \beta^2 - \alpha^2$$

$$B = 1/(b^2 + \beta^2 - 2b\alpha)$$

$$A = B[1 - 2B(b - \alpha)]$$

$$C = [B + A(b - \alpha)]/\Omega$$

$$D = -A \ .$$

An important quantity to be determined from the solution is the total mechanical energy delivered to the system

$$e - \frac{1}{2} m \dot{x}^2 + \frac{1}{2} kx^2 \ .$$

This quantity achieves a nearly constant value after the loading is completed.

ORGAN STRESS

In the case of the lung or the gastro-intestinal tract, the motion of the external body surface caused by blast loading is only the first step in a series of mechanical motions that eventually distort the organ of interest. Modeling of these intervening motions is required to correctly predict organ stress.

In the case of the larynx, however, the external motion and that of the injured tissue are very closely connected and so they will be taken as proportional to one another. More importantly, we shall assume that the opposing stresses that develop due to the body motion are proportional to the stresses in the injured tissue.

For the harmonic oscillator model, the body stress is given by the elastic force caused by displacement

$$\sigma = k x .$$

INJURY

The guiding principal behind the development of a mechanistic model is that damage occurs when the applied stress exceeds a biological material strength. Since biological materials are complex composites, the material properties may be equally complex. In particular, the limiting strength may be rate-dependent, anisotropic, or dependent on physiological conditions at the time of exposure. Only careful testing of the material can determine this. For the purposes of the generic model, however, we shall assume that there is a critical stress at which a particular level of injury occurs.

At the moment of maximum displacement or stress, the energy delivered to the body is completely contained in the potential energy of the elastic force

$$e = \frac{1}{2} k x^2 .$$

Therefore, the maximum elastic stress is related to the energy delivered by the blast loading by

$$\sigma = \sqrt{2ke} .$$

When this stress exceeds a value representing the material strength, it is assumed that irreversible damage will occur.

When a material is subjected to repeated stressing, it will fail by a process called fatigue [7]. The magnitude of the stress required decreases as the number of cycles increases. For many materials, the decrease in proportional to the logarithm of the number of cycles and can be represented as

$$\sigma(n) = \sigma(1) [1 - f \cdot \log(n)]$$

where the fatigue factor f depends on the material. Typical values for f are between 0.1 and 0.3.

The failure stress does not decrease without limit, however. Eventually, the ultimate stress, c_u, is reached, below which no amount of repetition will lead to failure. Typical values for the ultimate stress are shown below.

Material	$\sigma_u/\sigma(1)$
Steels	0.45-0.65
Wood	0.30
Concrete	0.50

We combine these results for simple materials into a model for injury to biological material as follows. The blast loading delivers energy to the body which is used to calculate the maximum elastic stress. The stress at which injury occurs is characterized by a failure stress for a single exposure and a fatigue factor that reduces the failure stress logarithmically for repeated exposures. Combinations of freefield blast conditions are found which lead to the system achieving the critical stress associated with a particular number of exposures. The locus of those points is the DRC.

3. COMPARISON WITH FIELD DATA

CLASSIFICATION OF INJURY

A considerable number of animal tests have been made to determine the occurrence of injury under various blast conditions. The grading of injury is somewhat subjective, however, and when combined with the variability of individual animals it is not possible to produce completely precise results. The scatter is only a matter of degree, however, and the trends with number and intensity of blast are unmistakable.

Two studies will be combined to give the data for calibrating and validating the generic model. In the work of Dodd et al. [8], the lowest levels of injury were sought in groups of six animals each in order to construct an occupational level DRC. The categories of injury used were as follows:

None	No injury in any animal
Trivial	Less than 30% of the group's animals having slight upper respiratory tract (URT) injury and no pulmonary or GI tract injury.
Unacceptable	Any animal with pulmonary or GI tract injury or more than 30% of the animals with URT injury or any single animal with moderate or severe URT injury.

In the work of Richmond [9], more serious injury was studied and the categories were

Slight	At least one, but not more than four, identifiable minor petechial hemorrhages.
Moderate	Single ecchymotic hemorrhage or more than four petechial hemorrhages.
Severe	Diffuse ecchymotic or petechial hemorrhages.

We will express the injury data in five categories: none, trivial, slight, moderate, and severe. Dodd's "unacceptable" is combined with Richmond's "slight."

SELECTION OF MODEL PARAMETERS

The blast waves will be assumed to follow the parameterization described earlier. Since the tests were conducted in Albuquerque, New Mexico, the atmospheric pressure is lower than at sea level.

$$b = 4$$

$$P_a = 82 \text{ kPa}$$

Three parameters must be chosen for the body. The musculature of the neck has the approximate density of water so that if it is 1 cm thick, the mass/area is about 10 kgm/m^2. The elastic strength and damping properties have not been measured so that arbitrary values will be assigned.

$$m = 10 \text{ kgm}/\text{m}^2$$

$$k = 4 \text{ kPa/mm} \quad \text{(corresponding to a vibration period of 10 ms)}$$

$$t_d = 100 \text{ ms} .$$

It was found that other combinations of body parameters and critical stress levels produced similar final injury predictions. This uncertainty can be cleared up with direct measurement of the material properties.

Finally, the critical stresses for damage must be chosen. Since there is no direct measure of these values, they must be assigned empirically. The fatigue factor is chosen to be similar to nonbiological materials.

$$f = 0.2$$

The stress levels separating each injury category were found by trial and error. The resulting parameter values are

$$
\begin{aligned}
\sigma(1) &= 69 \text{ kPa} \quad \text{(none to trivial)} \\
&= 109 \text{ kPa} \quad \text{(trivial to slight)} \\
&= 188 \text{ kPa} \quad \text{(slight to moderate)} \\
&= 295 \text{ kPa} \quad \text{(moderate to severe)}
\end{aligned}
$$

COMPARISON WITH DRC DATA

The comparison of the contours of critical stress in the body with the graded injury is shown in Figures 3-7. The field data is represented by the following symbols:

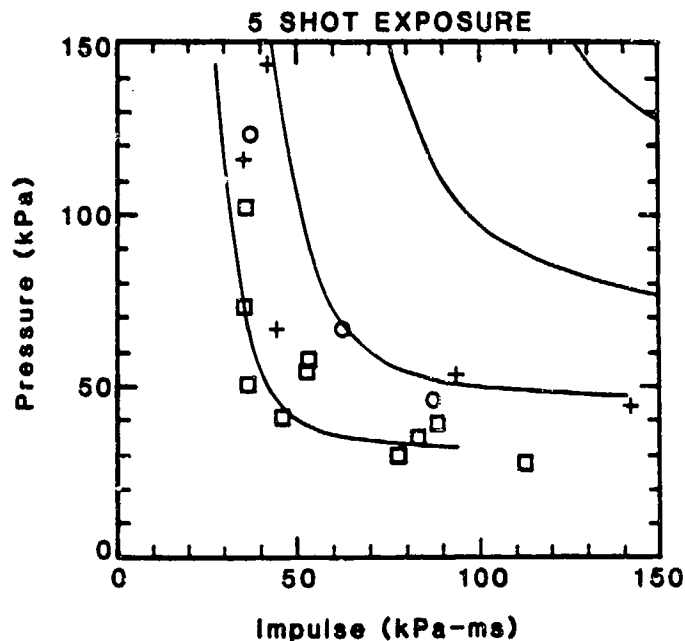|	
none:	open square
trivial:	open circle
slight:	+
moderate:	filled square
severe:	filled circle

Figure 3. Comparison of generic model predictions with data taken from [7] on observed larynx injury in sheep exposed to 5 shots. Symbols indicate observed injury level: □, none; o, trivial; +, slight; ■, moderate; •severe. Curves are equal stress contours based on the generic model for s(1) = 69 kPa, 108 kPa, 188 kPa, 295 kPa and a fatigue factor f = 0.2.
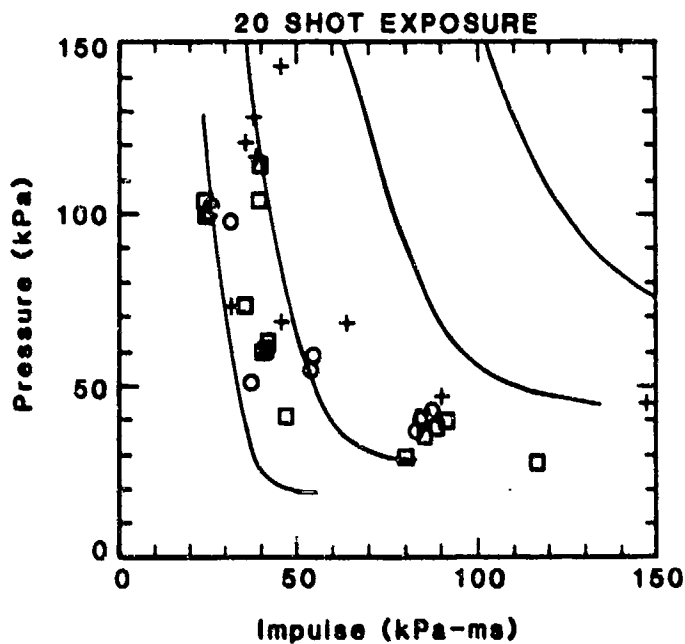

Figure 4. Comparison of generic model predictions with data taken from [7] on observed larynx injury in sheep exposed to 20 shots. See Figure 3 for explanation of symbols.
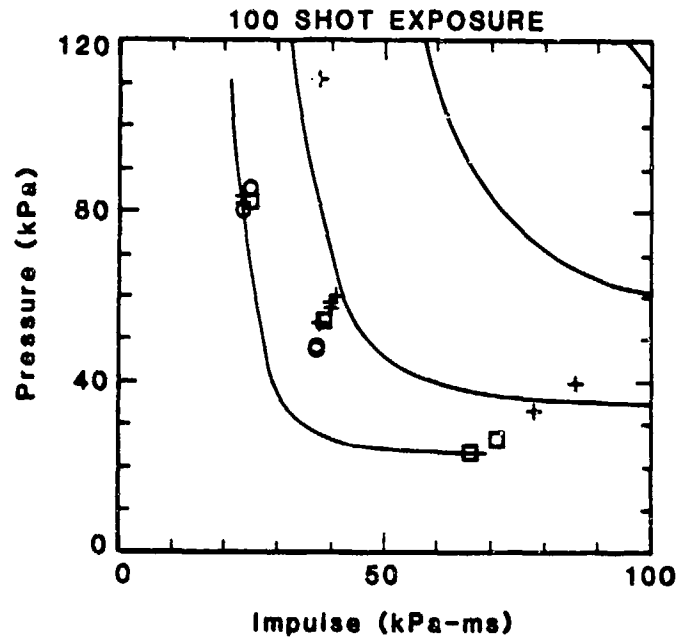
13

Figure 5. Comparison of generic model predictions with data taken from [7] on observed larynx injury in sheep exposed to 100 shots. See Figure 3 for explanation of symbols.
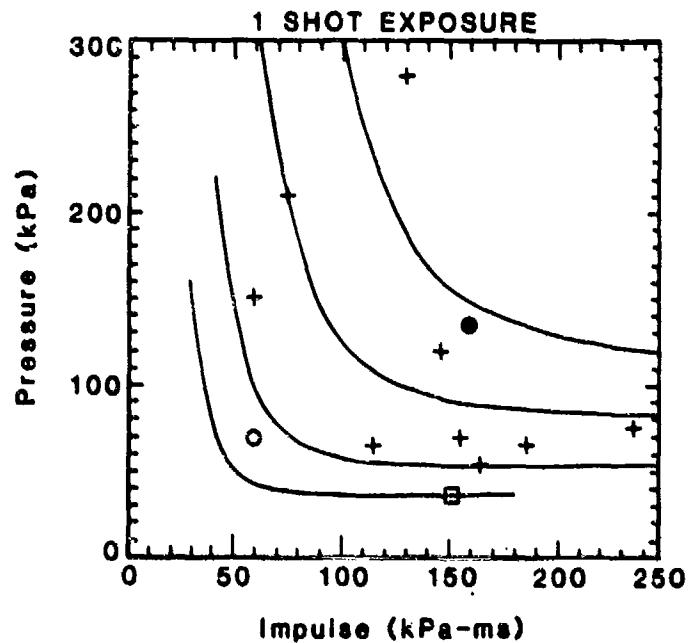

Figure 6. Comparison of generic model predictions with data taken from [8] on observed larynx injury in sheep exposed to 1 shot. See Figure 3 for explanation of symbols.
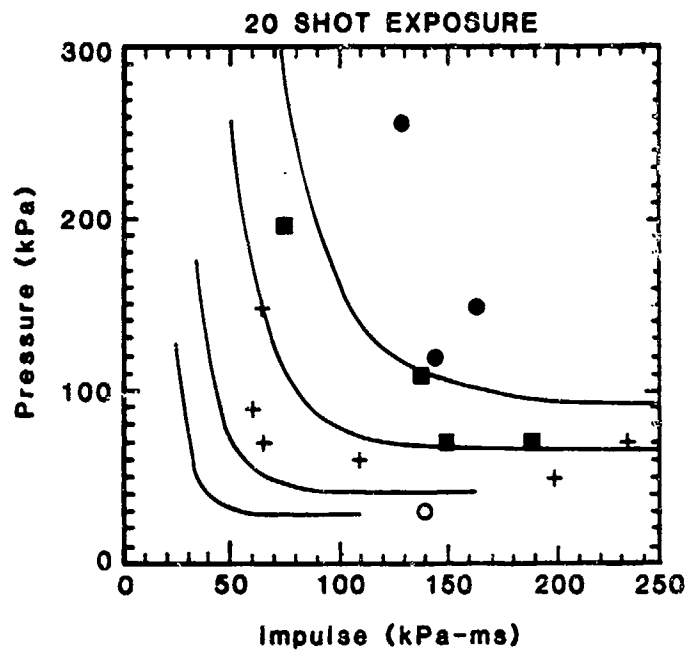
Figure 7. Comparison of generic model predictions with data taken from [8] on observed larynx injury in sheep exposed to 20 shots. See Figure 3 for explanation of symbols.

In each figure, the four contours shown correspond to the stress levels dividing the injury levels.

The model correlates the data reasonably well. Of the 92 data points shown, each of which represents from one to six animal exposures, 72 fall within corresponding stress limits, 12 show less injury than predicted by the stress level, and 8 show more injury than predicted. In each of the cases where the injury is greater than predicted, there are other data showing no injury at a greater stress level. These differences would seem to be due to animal variations that cannot be accounted for with the present level of measurement or modeling.

4. CONCLUSIONS

The model of blast injury presented above is able to correlate most of the observed laryngeal injury with stress produced in the body. The threshold stress level of 6f Pa with a fatigue factor of 0.2 provides a conservative prediction of the first occurrence of injury. That is, at 1, 5, 20, and 100 shot exposures, no injury is observed below the predicted level. The comparison with data is summarized in Figure 8. This relation provides the first analytical relation defining a Damage Risk Criterion for laryngeal injury.

The choice of material properties and critical stress is based on optimizing the correlation with data and so is not satisfactory as a predictive method for other species. Specific material properties have been identified, however, which can be measured in the laboratory and will allow the predictions to be extended.
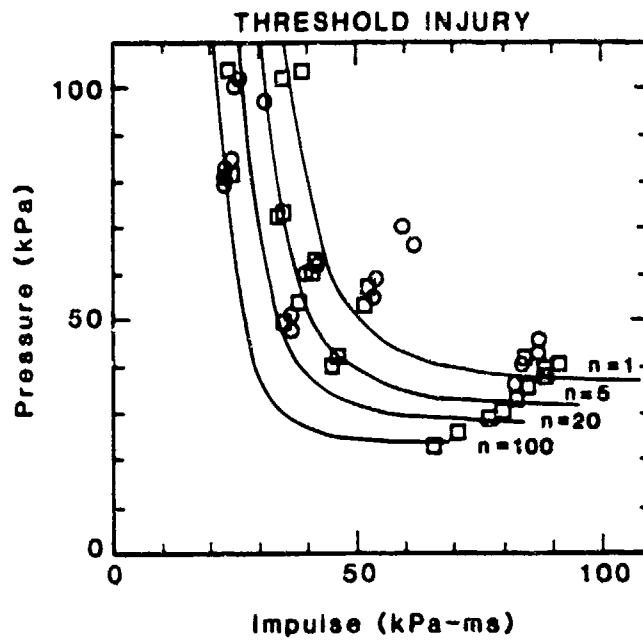
Figure 8. Damage Risk Criterion for threshold injury to the larynx based on the generic model described in the paper with a single shot critical stress of 69 kPa and a fatigue factor of 0.2. All injury observed lies to the right of the respective curves for 1, 5, 20, and 100 shot exposures.

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